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How Fertilizer Moves In Soils

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How Fertilizer Moves In Soils

D. K. CASSEL and E. H. VASEY

I. INTRODUCTION

During the past few years, concern about environmental quality has increased. This environmental concern is centered around such seemingly diverse subjects as water quality, air quality, proper land use, wise use of energy, etc. Many news releases have indicated that the quality of lake, stream and well waters in many areas has been degraded as a result of fertilizer use and/or misuse. Such reports have been substantiated in some areas of the United States, while in other areas their validity is questionable.

There is little doubt that deterioration of water quality as a result of fertilizer use occurs to some extent in certain areas. In the drier climates, i.e., sub-humid, semi-arid and arid zones, losses of fertilizer materials into water supplies may be of little importance. Nearly the entire state of North Dakota has a semi-arid climate.

Commercial fertilizers are currently recommended for spring or fall application by soil scientists at North Dakota State University. Some of the questions being raised about the fate of these commercial fertilizers include what happens to the fertilizer during the winter; during the spring; is it leached into the groundwater; is it removed in runoff waters in the spring? The discussion presented in this bulletin will attempt to answer these questions by discussing how fertilizers move in soils.

Fertilizer movement in soils is not a simple process. The term "fertilizer movement" includes both the movement of *dissolved* fertilizers or their products through soils by water (or in some cases over the soils in runoff water), and the transport of *solid* fertilizers or their products during water-caused soil erosion. Emphasis will be placed on the movement of dissolved fertilizers. Many factors, working together in a complex manner, influence the behavior and movement of fertilizers in soils. Only the more important factors will be discussed.

Since water must be present in or on the soil before fertilizer movement can be initiated, we must first look at the hydrologic (water) cycle for North Dakota. Understanding the fate of precipitation received is the first step toward understanding fertilizer movement. The hydrologic cycle is treated in Section II.

Soil properties are extremely important in understanding fertilizer movement in soils. Each soil type differs from others in one or more soil properties. A discussion of selected chemical and physical soil properties is presented in Section III.

Section IV covers the chemical nature of the fertilizer material itself. The chemical form of a fertilizer dictates, to a certain degree, the ultimate fate of that fertilizer. For example, some fertilizers or their products are retained by soil particles while others are not.

The manner in which a given soil is managed is important. The effect of soil management (e.g., irrigation, fallowing, continuous cropping) upon fertilizer movement is presented in Section V.

A number of practical examples of fertilizer movement for common field situations encountered in North Dakota agriculture are presented in Section VI. In order to understand why fertilizers behave in soils as they do, we must draw on our discussion in Sections II through V. In summary, the results of the previous sections are integrated to arrive at an understanding of how fertilizer behaves for a wide range of practical situations.

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II. HYDROLOGIC CYCLE

A. Precipitation

The mean annual precipitation in North Dakota (Figure 1) ranges from 20 inches in portions of the

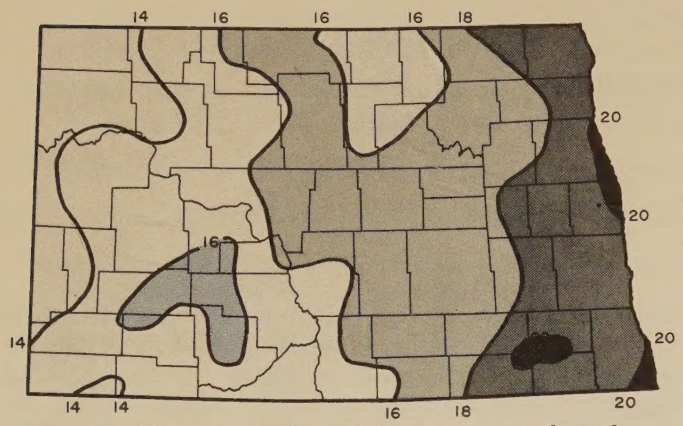


Figure 1. Mean annual precipitation in North Dakota.

Red River Valley in the eastern part of the state to 13 inches in the northwest. Seventy-five to 80 per cent of this precipitation occurs during April to September, with most of it falling in May, June and July. Much of the remaining 20 to 25 per cent of the precipitation which falls from October through March may occur as snow, which may remain on the soil surface until the spring or mid-winter thaw.

The total amount of precipitation falling upon the earth's surface is important, but possibly of more importance, from the standpoint of fertilizer movement, is the fate of the precipitation once it reaches the soil surface. Figure 2 presents a schematic of the hydrologic cycle. For the present, let us consider only that precipitation falling as rain upon unfrozen soil. Immediately upon reaching the soil surface the water may enter the soil (infiltrate), be temporarily stored in small depressions on the soil surface or be lost as runoff.

B. Runoff

The contour lines in Figure 3 indicate the minimum amount of runoff expected in North Dakota for five years out of any 10-year period. The data is based on U. S. Geological Survey stream gauging stations (watersheds ranged from 17-250 square miles in size). For five years of a 10-year period, runoff will not be as great as indicated by the contour lines; during the other five years runoff will be the amount indicated or greater. The diagonal straight lines indicate the percentage of total runoff that results from snow melt waters. The quantity of water lost as runoff from a particular field in the watershed is determined in part by the amount, intensity (rate) and duration of the rainfall, as well as the slope, texture and permeability of the soil. As rainfall intensity increases, the likelihood increases for a greater amount of runoff and associated soil erosion. Similarly, as the duration and/or the amount of rainfall increases, more runoff and erosion are expected.

The presence of vegetative cover or a *plant canopy* on the soil surface serves as protection which reduces the impact of raindrops on the soil surface. The net effect of the presence of the plant canopy is to reduce surface runoff and associated erosion. This plant canopy effect becomes extremely important in reducing soil erosion during and after intense thunderstorms like those commonly experienced during the summer months.

C. Infiltration and Storage of Water in the Soil Profile

If the rainfall is trapped in a depression on the soil surface it is temporarily stored until it is either evaporated or it infiltrates the soil. As water enters the soil it is stored in the crop rooting zone until

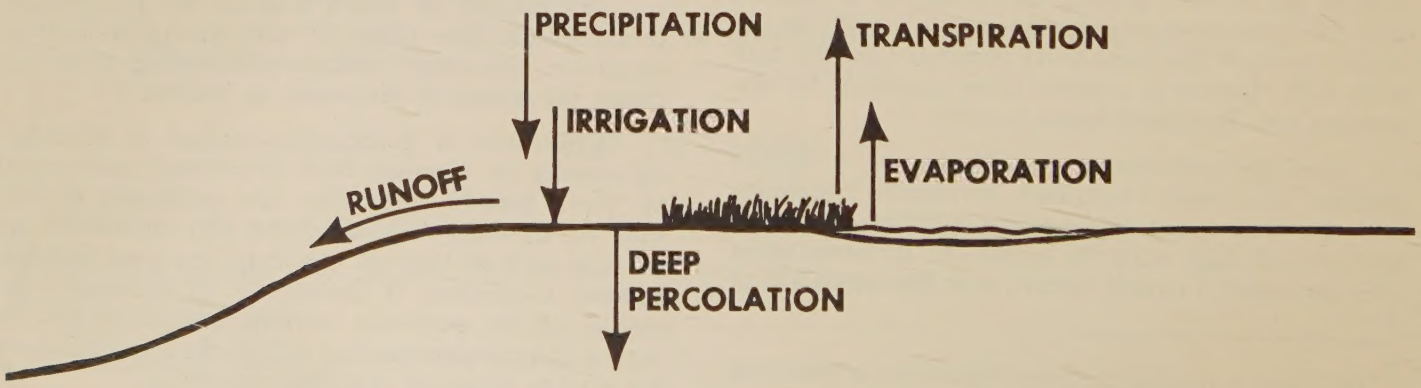


Figure 2. Schematic of hydrologic cycle.

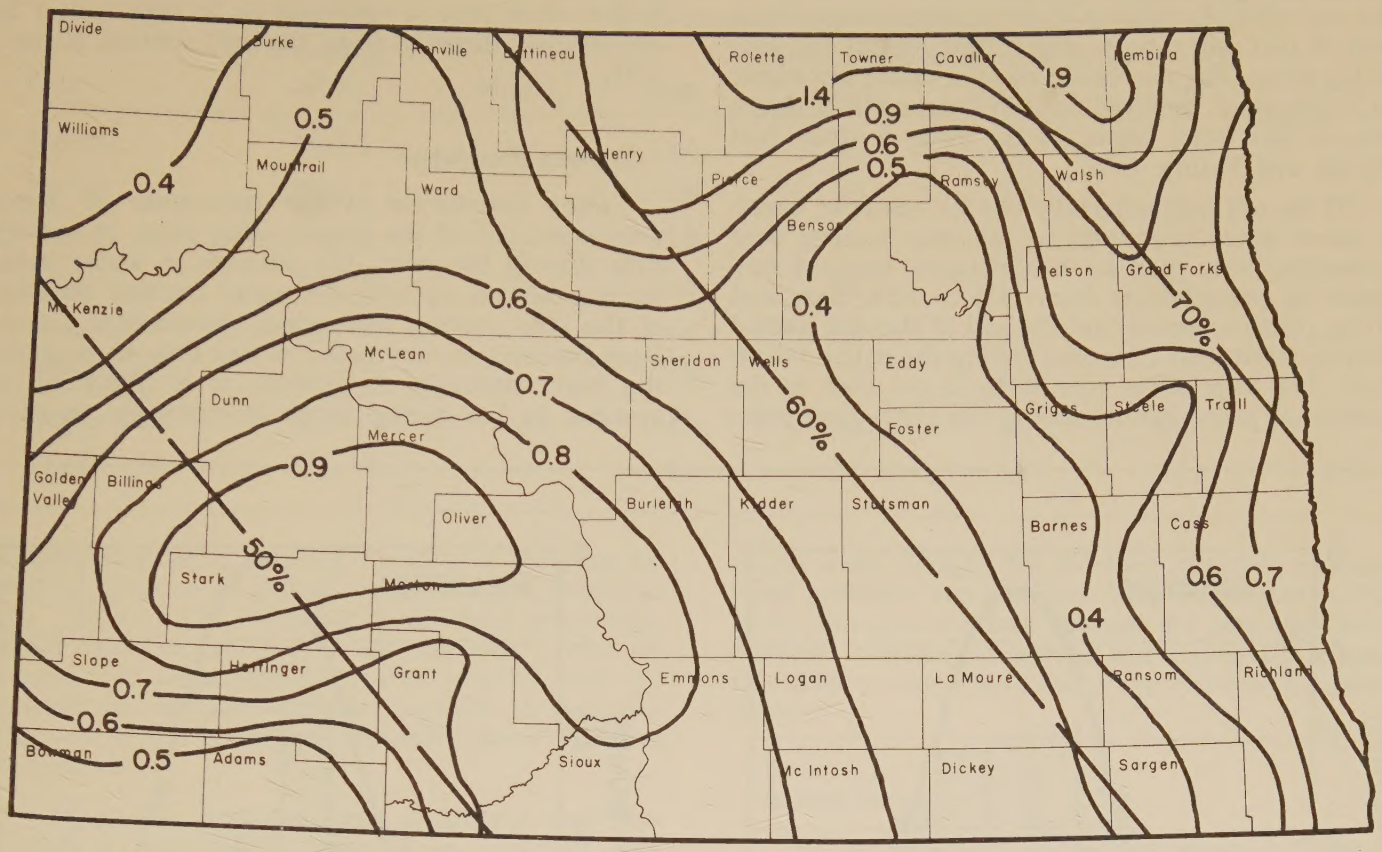


Figure 3. The minimum surface runoff expected (contours) and per cent of this runoff coming from snow melt water (diagonal line) for five out of 10 years. Runoff will be less than the amounts indicated five of these years; for the remaining five years, runoff will be equal to or greater than the amounts indicated. (Map based on data collected through 1971 and provided courtesy of Soil Conservation Service, Bismarck, North Dakota).

the *water holding capacity* is filled. Water added either as precipitation or irrigation in excess of water holding capacity may be lost by deep percolation. Infiltration rates and water holding capacities of soils vary greatly and will be treated in more detail in Section III.

D. Evapotranspiration

Water present on the soil surface can be lost to *evaporation*. Water stored in the plant rooting zone can be lost either to evaporation directly from the soil surface or extracted by plant roots, passed through the plants and evaporated into the atmosphere through the plant leaves — a process called *transpiration*.

Evapotranspiration is defined as the total water lost to the atmosphere by the combined processes of evaporation and transpiration. Another term necessary for this discussion is *potential evapotranspiration* (PET), which is the amount of water which can be evaporated into the atmosphere from a free water surface such as a lake under the prevailing atmospheric conditions. Figure 4 compares monthly PET computed by the Thornthwaite method (Thornthwaite, 1948) with mean monthly precipitation for four locations in North Dakota for the 1941-70 period. The potential evapotranspiration is somewhat similar for the entire state, while the mean monthly precipitation varies considerably from location to location.

It is fortunate that most of the rainfall occurs at a time when PET or the demand for water by plants is at a maximum. It is obvious from Figure 4, however, that in May through September the atmosphere has the potential to evaporate more water from a cropped field than is received as precipitation during the same months. During this period, water stored in the crop rooting zone is used to help meet this evaporative demand. If all water leaves the crop rooting zone, drought results.

During the early part of the growing season, annual crops extract most of their water from the topsoil, while water in the subsoil remains stored until later in the growing season. Estimated crop

rooting depths for several crops at selected times during the growing season are shown in Table 1. For example, the rooting depth for corn ranges from zero at planting time to about four feet at the ear-filling stage. The maximum rooting depth for wheat on moderately well and well drained soils in North Dakota has been found to be three to four feet (Bauer and Young, 1969).

If the soil is summerfallowed for one year, usually more water is present in the crop rooting zone at seeding time than for a continuous cropped soil. Based on observations from 1915 to 1954, Haas and Willis (1962) reported that the soil at Mandan gained only an additional 1.7 inches during the entire fallow year. This represents only 10 to 15 per cent of the additional precipitation during the uncropped year. The remainder of the precipitation was lost to run-off, evaporation or deep percolation. Water stored in the upper foot of soil tends to be rapidly lost by evaporation directly from the soil surface (Cassel, 1971).

E. Deep Percolation

Deep percolation is the movement of water downward out of the crop rooting zone. If, at any time during the year, the amount of water infiltrating the soil exceeds the water holding capacity of the crop rooting zone, deep percolation occurs. Deep percolation may occur at any time throughout the year, although, in general, it is likely to be greatest in the spring when precipitation exceeds

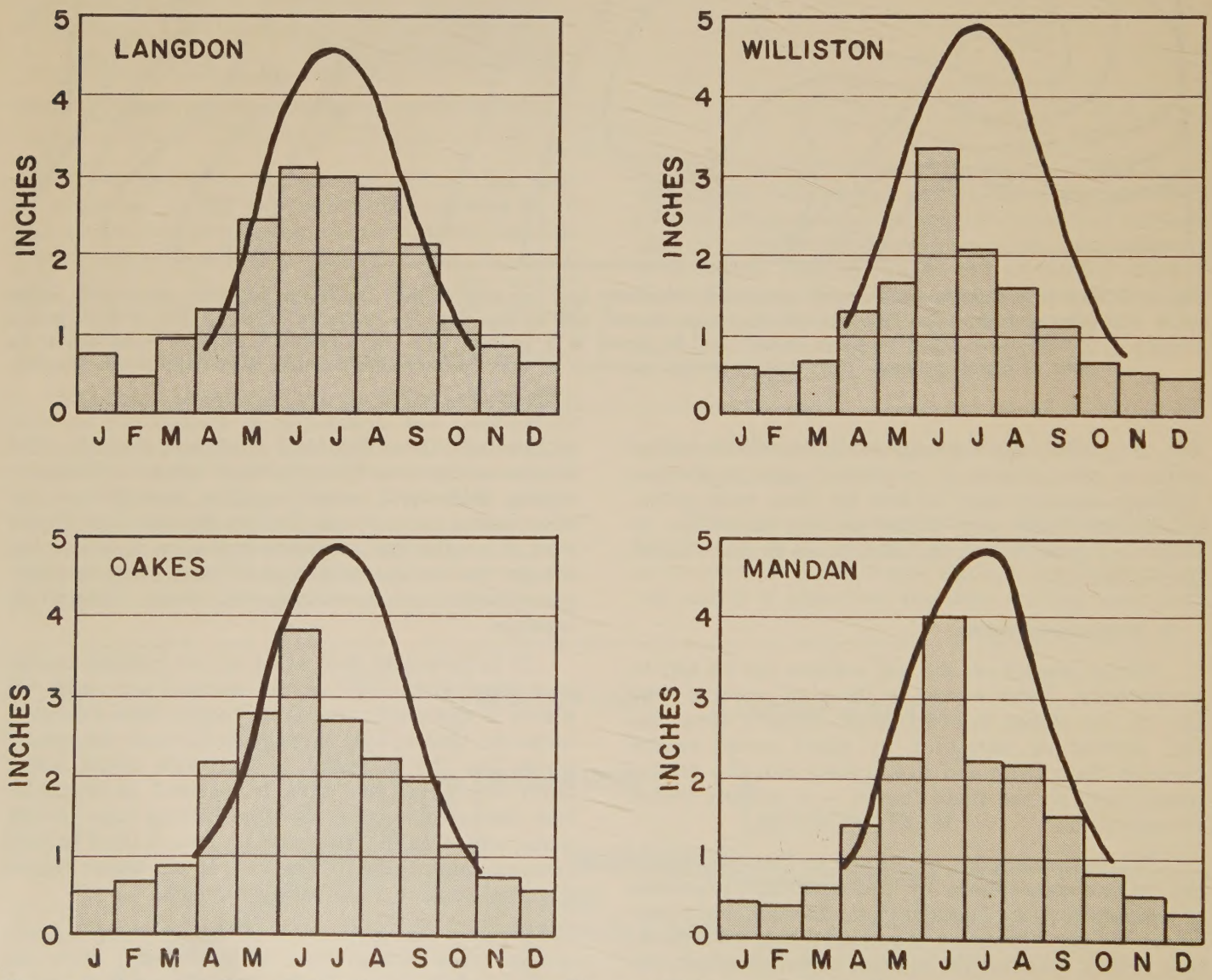


Figure 4. Mean monthly precipitation and mean monthly potential evapotranspiration calculated by the Thornthwaite Method for four locations in North Dakota.

Table 1. Estimated Average Crop Rooting Depths at Several Dates for Selected North Dakota Crops.

Crop	Average Planting Date	Approximate depth of substantial root extraction of water for various dates (feet)					
		May 1	June 1	July 1	Aug. 1	Sept. 1	Oct. 1
Wheat	May 1	—	1.5	3.0	3.0	—	—
Barley	May 1	—	1.5	3.0	3.0	—	—
Oats	May 1	—	1.5	3.0	3.0	—	—
Corn	May 20	—	0.5	2.5	4.0	4.0	—
Potatoes	May 5	—	0.5	1.0	1.5	1.5	—
Soybeans	May 20	—	0.5	1.5	2.0	2.0	—
Sugar beets	May 15	—	1.0	2.5	4.0	4.0	—
Sunflowers	May 25	—	0.5	1.5	2.0	2.0	2.0

evapotranspiration. During this time of the year the rooting systems of annual crops are not extensive (see Table 1). On the other hand, deep percolation could occur in late July if several heavy rains occurred and infiltration of water into the soil exceeded the amount of water required to replenish the soil water previously extracted from the crop rooting zone.

Up to this point we have considered only precipitation occurring as rainfall on unfrozen soil. If the precipitation occurs as sleet or snow, a portion of it probably will be lost to runoff or, depending upon soil conditions, it may infiltrate the soil. Fifty per cent or more of the runoff indicated in Figure 3 occurs as a result of snow melt waters running off during the spring thaw. The amount of runoff at this time tends to increase as the amount of accumulated snowfall increases.

III. SOIL PROPERTIES

Fertilizer movement in two different soils, only a few hundred feet apart, may be appreciably different even though the weather and soil management practices are identical. This difference in fertilizer movement arises because the two soils have different physical, chemical and biological properties. Several important soil properties are discussed below.

A. Soil Texture

Soil texture refers to the coarseness or fineness of a soil. More specifically, it refers to the relative proportions of sand, silt and clay particles. The size limits of these soil fractions and the surface area per unit weight of particles are given in Table 2. The amount of surface area in a soil determines its physical properties and many of its chemical properties. Sand grains are relatively large but have a small *specific surface* (surface area per unit weight of soil particles). Individual clay particles, on the other hand, are extremely small but collectively exhibit an enormous specific surface. Since the clay fraction has much more surface area than an equivalent weight of silt or sand particles, the clay fraction exerts a greater influence on the soil properties than do the silt and sand fractions. Hence, we see

Table 2. Effective Diameter and Surface Area Per Unit Weight of Sand, Silt and Clay.

Soil fraction	Effective diameter (in)	(mm)	Surface area per unit weight (cm^2/gm)
Coarse sands	0.08-0.02	2.0-0.50	11-45
Medium sands	0.02-0.01	0.50-0.25	45-91
Fine sands	0.01-0.002	0.25-0.05	91-453
Silt	0.002-0.0008	0.05-0.002	453-11321
Clay	less than 0.0008	less than 0.002	greater than 11321

that the relative proportions of sand, silt and clay; i.e., the soil texture, becomes important. Soil textural classes shown in Table 3 are convenient groupings of soil textures (Soil Survey Manual, 1951). Reference to soil textural classes will be made throughout this bulletin.

Table 3. Soil Textural Classes

Textural Class	Texture	
Sands Loamy sands	Coarse	Sandy
Sandy loam Fine sandy loam	Moderately coarse	
Very fine sandy loam Loam Silt loam Silt	Medium	Loamy
Clay loam Sandy clay loam Silty clay loam	Moderately fine	
Sandy clay Silty clay Clay	Fine	Clayey

Soil texture in a given soil profile usually varies with depth. For example, a soil may be clay loam (moderately fine texture) in the upper one foot of the crop rooting zone and loam (medium texture) below a depth of one foot. Indirectly, soil texture has a great influence on water retention properties and the ability of a soil to retain certain fertilizer constituents. These properties will be discussed further.

B. Soil Structure

Soil structure refers to the arrangement of the sand, silt and clay particles into aggregates of various shapes and sizes, and to the stability of these aggregates. Coarse-textured soils have a tendency to be structureless; i.e., each soil particle acts independently of others. As the per cent clay increases, the clay particles act as a cementing agent which helps to bind the individual soil particles together. Organic matter present in the soil and mucilages and gums produced by micro-organisms also act as cementing agents. Destroying large cracks in the surface soil by plowing or by a tillage operation alters the structure of the soil surface, which in turn can affect solute movement, especially under saturated conditions. *Saturation* refers to the condition when all soil pores or voids are filled with water.

C. Water Holding Capacity

Water holding capacity of a soil is greatly influenced by soil texture and by the amount of organic matter present in the soil. Water holding capacity increases along with organic matter. In general, the amount of organic matter in a soil decreases with depth. Figure 5 shows the manner in which the water holding capacity changes with soil texture. Water holding capacity values range from a minimum of about 0.6 inches of water per foot for sand to a maximum exceeding 4.5 inches per foot for fine-textured soils. Of these amounts only the water labeled "available" in Figure 5 can be extracted by plants.

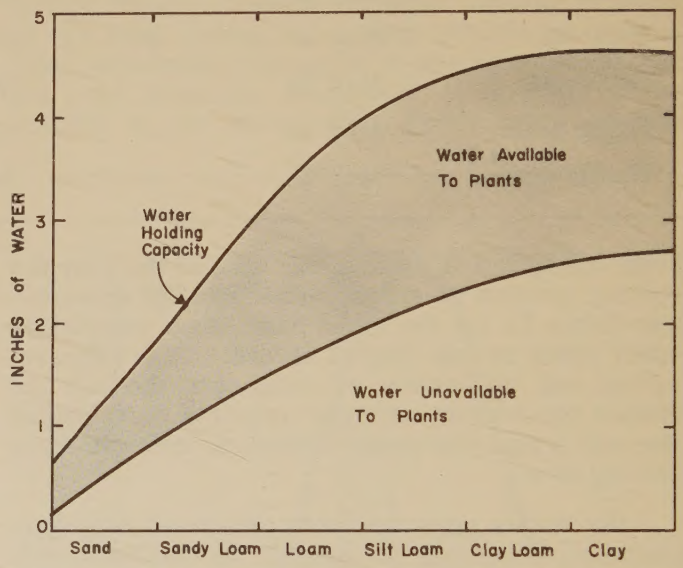


Figure 5. Influence of soil texture on water holding capacity.

The amount of available water increases as texture becomes finer only up to the medium to moderately fine-textured soils. From this point, available water decreases with fineness of texture. "Unavailable" water is related to the amount of clay and organic matter present and is held in the soil so strongly that plant roots cannot exert enough energy to extract it. Nearly all movement of fertilizer salts in soils occurs when "available" water is present.

As stated before, soil texture varies with depth. As soil texture changes, then so does water holding capacity change with depth. The water holding capacity of the upper part of the crop rooting zone may be greater or less than the lower portion, depending upon the combined effects of soil texture and the amount of organic matter present.

D. Position of Soil on Landscape (Slope)

The position of a given soil on the landscape or the *soil slope* is an important factor affecting the movement of fertilizers in soils. Soils in low-lying areas tend to be finer textured and have more organic matter than nearby soils with steeper slopes. Hence, the soils in low areas tend to hold more water. Soil slope is important with regard to the fate of precipitation after it reaches the soil surface. Nearly level soil holds the precipitation, with most of it infiltrating the soil. As the landscape becomes steeper, more of the precipitation may be lost to runoff. Moreover, some soil erosion occurs with an associated loss of fertilizer solids and nutrients held on the soil particles. Soils in the low-lying areas tend to be wetter because they are nearly level and receive runon water. Temporary or permanent potholes may result when the low areas are closed depressions.

E. Soil Water Permeability and Infiltration Rate

Soil water permeability is defined as the rate at which a *saturated* soil transmits water, and this is influenced greatly by soil texture and soil structure. Soil permeability classes are presented in Table 4. Although exceptions do exist, fine-textured soils have slow or very slow permeability, while coarse-textured soils tend to have very rapid or rapid permeability. A medium-textured soil, such as loam, has moderate or moderately slow permeability. *Infiltration rate* is closely related to the permeability and is defined as the rate at which water enters the soil surface. Infiltration rate is influenced by the permeability of different horizons or soil layers in the soil profile and the amount of water already present in the soil. It cannot exceed the permeability of the least permeable layer when the soil is saturated.

Percolation of precipitation or irrigation water and associated leaching of soluble fertilizer salts readily occur for coarse-textured soils which have low water holding capacities (Figure 5), and which allow water to flow through rapidly (Table 4). Medium-textured soils have greater water holding capacity and moderate percolation rates, thus reducing percolation losses. Even though the water holding capacity of fine-textured soils is nearly the same as for medium-textured soils, the slow to very slow percolation rates of the fine-textured soils may result in appreciably more runoff. If a fine-textured soil has a nearly level slope and is located in a low-lying area, it may receive *runon* water and remain wet much of the time.

Table 4. Saturated Soil Water Permeability Classes (Guide for Interpreting Engineering Uses of Soils)

Soil Permeability (inch/hr)	Class
less than 0.06	very slow
0.06 to 0.2	slow
0.2 to 0.6	moderately slow
0.6 to 2.0	moderate
2.0 to 6.0	moderately rapid
6.0 to 20	rapid
more than 20	very rapid

F. Nature of the Clay Fraction

The clay fraction is composed of many kinds of inorganic clay minerals of which the dominant one in North Dakota soils is *montmorillonite*. This clay mineral is characterized by expanding in size as it becomes wet and shrinking as it dries. In addition, this clay mineral takes credit for the cracks one observes in many soil surfaces as they dry.

Each clay particle has a residual electric charge — this residual electric charge is *negative*. These sites of negative charge are extremely important in many chemical processes occurring in the soil. It is this residual charge on clay particles (and on particles of organic matter) which causes some of the fertilizer constituents or their derivatives to be *adsorbed* to (held to) the surfaces of clay particles and thus remain in the soil even though water may be flowing through the soil. The constituents that are *adsorbed* have positive charges on them and are called *cations*. On the other hand, this same negative residual charge repels negatively charged fertilizer constituents *(anions);* in this case, water flowing through a soil would *leach* or move the constituents down out of the rooting zone. The total amount of residual negative charge per 100g (3.5 ounces) soil is defined as the *cation exchange capacity* (CEC). As the CEC increases, the ability of the soil to retain more cations increases. For very coarse-textured soils, the CEC is low and the loss of cations by leaching may occur simply because the storage capacity for cations is not great enough to retain all of the cations present in the soil. For example, excessive potassium cations may be leached from coarse-textured soils because it has a low CEC as a result of few clay particles and/or little organic matter being present.

IV. NATURE OF FERTILIZER MATERIALS

The amount of commercial fertilizer used in North Dakota has increased quite steadily from 1950 to 1972. Figure 6 shows the trend. Figure 7 breaks the data down into values for elemental nitrogen, phosphorus and potassium. The increase in fertilizer

consumption is one of the reasons that fertilizer use is at times associated with reports of degraded water quality. Table A in the Appendix shows the amounts of blends and materials sold in North Dakota during 1972.

The nutrients nitrogen, phosphorus, and potassium have different types of reactions when applied to soils. Let us consider these reactions for each of these nutrients.

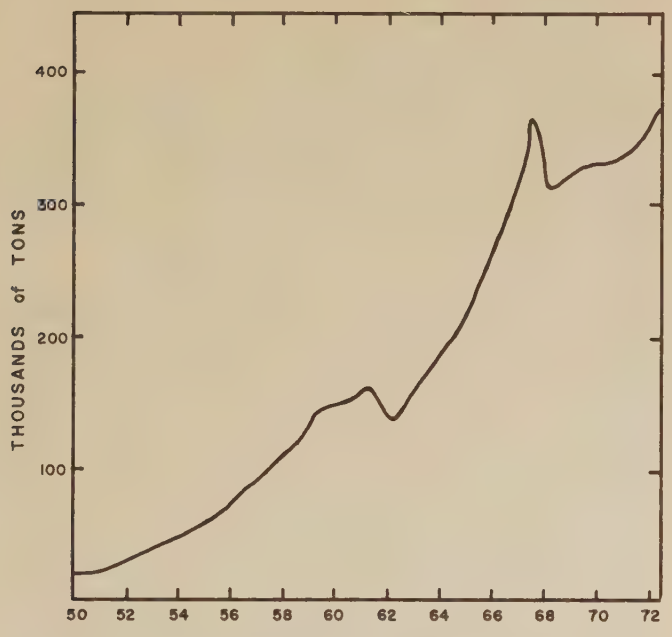


Figure 6. Commercial fertilizer consumption in North Dakota from 1950 to 1972.

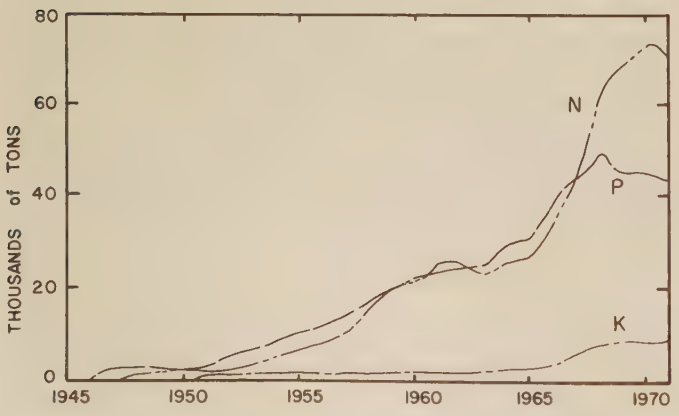


Figure 7. Tons of elemental nitrogen, phosphorus and potassium added North Dakota soils in commercial fertilizers from 1950 to 1971.

A. Nitrogen

The majority of nitrogen is present in North Dakota soils as organic matter. This organic matter reserve has been the main source of available nitrogen for crop production. The organic matter itself is not available for plant use. Part of this reserve has been used up through crop removal. This is evidenced by a decline of at least 30 per cent in total soil organic matter and nitrogen as a result of more than 40 years of cropping.

Cool soil temperatures associated with our climate, especially in early spring, result in comparatively slow release of available nitrogen from organic matter in our soils. As a result, our soils often are relatively high in natural organic matter, but the available nitrogen is not made available fast enough for the growing crops. For this reason profitable responses to fertilizer nitrogen are obtained, especially on early seeded, early maturing crops grown on non-fallow land. The practice of summerfallow allows longer periods of time for the accumulation of available nitrogen. Even after summerfallow, some soils may contain inadequate available nitrogen for crop production because the reserves of organic matter have been depleted or because climate limits the conversion of organic nitrogen to available forms.

Yearly variability in moisture and temperature causes variation in amounts of nitrogen released from organic matter. Nitrogen needs for crops also vary with the crop as well as with growth and yield potential limitations imposed by soils and annual variations in growing conditions (if climatic conditions limit yield to 15 bushels per acre the need for nitrogen is not as great as that needed by climatic conditions allowing 40 bushels per acre production). Such variability in supplies and need for available soil nitrogen makes it a somewhat difficult task to predict supplemental fertilizer nitrogen needs at rates that always give the greatest return (Dahnke and Vasey, 1973). Available nitrogen as nitrate (NO_3-N) level present in the soil and realistic yield expectations based on management decisions presently provide fairly accurate fertilizer nitrogen rate recommendations.

THE NITROGEN CYCLE

The basic portions of the nitrogen cycle are shown in Figure 8. A more complete representation can be found in various books, such as Soil Fertility and Fertilizers, 1966.

Mineralization of organic nitrogen compounds: The organic nitrogen contained in organic matter cannot be used by plants. The breakdown or decomposition of organic nitrogen compounds often is called mineralization. This mineralization process takes

place in several phases and numerous groups of bacteria and fungi are responsible for one or more of the steps involved in organic matter decomposition. The end product of one group's activity is the starting point for another group until decomposition reaches final stages. Ammonia (NH_3) is released at the end of the first phase of this mineralization process. This is *ammonification.*

The ammonia (NH_3) so released undergoes rapid conversion to the ammonium ion (NH_4^+) which may be used in one of several ways: (1) converted to nitrite (NO_2^-) and nitrate (NO_3^-), (2) absorbed by plant roots, (3) absorbed by micro-organisms for further decomposition of organic carbon residues *(immobilization),* or (4) fixed in unavailable forms. Most of the NH_4^+ is converted to NO_3^-. This biological oxidation of ammonium to nitrate is *nitrification.*

It is important to recognize that the above reactions all involve microbial activity, and as a result the rapidity and extent to which they occur are greatly influenced by soil environmental conditions such as soil reaction (pH), soil aeration, soil moisture, and soil temperature. In general, the environmental factors favoring good growth of most plants also favor high organism activity. The fact that nitrification requires gaseous oxygen means that it occurs most readily in well-aerated soils.

Because the ammonium ion (NH_4^+) carries a positive charge means it can be adsorbed and held by the negative charge on clay minerals and organic matter particles. As a result, it is not as subject to leaching losses as is the nitrate form, provided the soil has sufficient exchange capacity to hold it. Nitrate, on the other hand, carries a negative charge, is mobile in soil and moves largely with the soil water. The recommendation often seen in farm magazines about waiting until soil temperatures are 50°F or lower before applying nitrogen fertilizer in the fall relate to these characteristics of ammonium

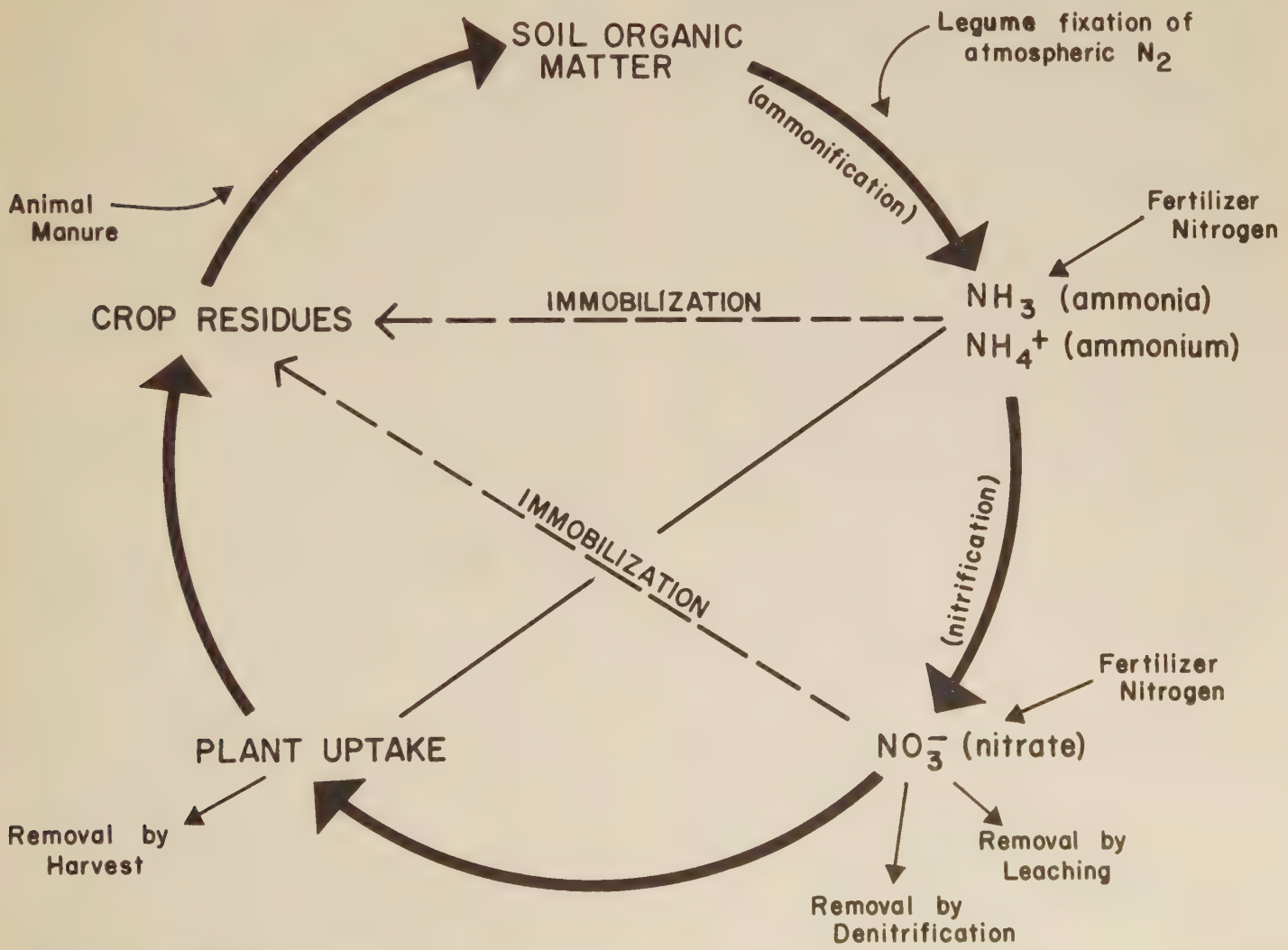


Figure 8. Simplified nitrogen cycle.

and nitrate. Ammonium applied at these temperatures will not undergo much conversion to nitrate; thus it is held on particles and not subject to leaching by the fall and winter rainfall received in the areas where the recommendation applies. Possible leaching losses of the NO_3^- and NH_4^+ are considered in detail in Section VI.

Losses of available nitrogen from soils occur in a variety of ways, some of which are:

1. *Leaching* - This process is discussed in detail in Section VI.

2. *Surface runoff* - Fertilizer nitrogen broadcast on frozen soil, especially if broadcast on snow or ice, could be lost in the spring runoff.

3. *Erosion* - Any removal of solid soil material will result in losses of nitrogen from soil.

4. *Denitrification* - Substantial amounts of available soil nitrogen can be rapidly changed to unavailable atmospheric nitrogen (N_2) when soil is *waterlogged* or saturated. Such denitrification is carried out by bacteria that thrive when there is no gaseous oxygen present in the soil. Significant losses by this means can occur where water stands on a field for several days or more. This is another reason for avoiding fall broadcast of nitrogen fertilizers where ponding may occur in the spring.

5. *Volatilization* - Ammonium salts in a wet, alkaline (pH above 7) soil undergo a chemical reaction resulting in the escape of ammonia nitrogen. If fertilizer materials containing ammonium nitrogen are placed on the surface of alkaline soils (our soils often are on the alkaline side with pH above 7), free ammonia may be lost. This loss can be prevented by placing the nitrogen material several inches below the soil surface (anhydrous ammonia, aqua ammonia) or incorporating them into the soil within 3 to 5 days after application (broadcast dry or non-pressure liquids). These losses are increased under conditions of high soil temperatures and rapid evaporation of water.

Nitrogen Fertilizers

The primary nitrogen fertilizers used in North Dakota are as follows:

Name of Fertilizer	Chemical formula	Usual analysis	Form
Ammonium nitrate	NH_4NO_3	33.5-0-0	solid
Anhydrous ammonia	NH_3	82-0-0	gas
Urea	$NH_2 \cdot CO \cdot NH_2$	45-0-0	solid
Ammonium sulfate	$(NH_4)_2SO_4$	20-0-0	solid
Nitrogen solutions	Mixture of urea and ammonium nitrate	28 to 34-0-0	liquid

A look at the basic production for these various fertilizer materials will show in what form they enter the nitrogen cycle and how they react once they have been applied.

The production of synthetic ammonia in the United States constitutes by far the principal original source of all chemical nitrogen fertilizers. The basic reaction is:

$$3H_2 + N_2 \longrightarrow 2NH_3$$

This reaction produces anhydrous ammonia, which contains the highest percentage of nitrogen (82%) of any nitrogenous fertilizer now available. Since no further processing is needed after its manufacture, it can be sold at a very attractive price. Once it is in the soil it converts rapidly to the ammonium ion (NH_4^+) and enters the nitrogen cycle as this form.

Ammonia can be oxidized to nitric acid (HNO_3). This nitric acid is then used in the manufacture of ammonium nitrate as follows:

$$HNO_3 + NH_3 \longrightarrow NH_4NO_3$$

It enters the nitrogen cycle as the NH_4^+ and NO_3^- form. Since one half of the nitrogen in ammonium nitrate is ammonium, volatilization losses can occur when improperly applied to alkaline soils. For this reason it is suggested that it be incorporated into soils within 3 to 5 days.

Ammonia also can be reacted with sulfuric acid to form ammonium sulfate as follows:

$$2NH_3 + H_2SO_4 \longrightarrow (NH_4)_2SO_4$$

This material contains 20.5 per cent nitrogen and 24.2 per cent sulfur. It enters the nitrogen cycle as NH_4^+.

Another nitrogen material made from ammonia is urea. This is made by reacting ammonia with carbon dioxide as follows:

$$CO_2 + 2NH_3 \longrightarrow CO(NH_2)_2 + H_2O$$

Urea contains the highest percentage of nitrogen (45%) of any solid nitrogen material now available. It is not an ammonium-containing fertilizer when marketed, but hydrolyzes to ammonium carbonate very quickly upon addition to soil as follows:

$$CO(NH_2)_2 + 2H_2O \longrightarrow (NH_4)_2CO_3$$

Ammonium carbonate is unstable and breaks down to yield ammonia and carbon dioxide as follows:

$$(NH_4)_2CO_3 \longrightarrow 2NH_3 + CO_2 + H_2O$$

This rapid *hydrolysis* means that if urea is applied to the soil surface or to sod, volatilization losses of ammonia may be significant.

Aqua ammonia is made by dissolving anhydrous ammonia in water. Nitrogen solutions are made by dissolving materials such as ammonium nitrate and urea in water or aqua ammonia. All nitrogen solutions are classified as *pressure solutions* (have a vapor pressure because free ammonia is present) or *non-pressure solutions* (contain no free ammonia). Pressure nitrogen solutions, like anhydrous ammonia, should be applied in, not on, the soil. Non-pressure nitrogen solutions are more commonly used in North Dakota, with 28-0-0 being the most common one. This is a mixture of ammonium nitrate and urea dissolved in water.

Nitrogen Summary

Several things about nitrogen behavior in soils are noteworthy. Nitrogen added to soils as commercial N fertilizers are the same forms that occur naturally in the nitrogen cycle. Regardless of the form of soluble nitrogen fertilizer added to the soil, it undergoes conversion to nitrate rather quickly if the soil is warm and moist.

The nitrate form of nitrogen is not attracted to soil particles and thus is free to move with the soil water. Significant losses of fertilizer nitrogen usually occur from improper use.

B. Phosphorus

This nutrient usually is expressed as phosphorus pentoxide (P_2O_5) in fertilizer analyses, but does not exist in that form. The expression P_2O_5 is a carry-over from the time when phosphorus determinations were made by oxidation of phosphorus. Phosphorus is expressed as elemental phosphorus (P) in this publication.

Phosphorus is never found in nature as the element (P), but is combined with other elements into minerals such as the *apatites*. Rock phosphate contains apatites and is heat-treated or acid-treated to render the phosphorus more soluble. Rock phosphate is the starting point of commercial phosphorus fertilizers and has been used as a fertilizer in untreated form. Phosphorus also is found in organic compounds.

Phosphorus is taken up by plants largely as the primary and secondary orthophosphate ions $H_2PO_4^-$ and $HPO_4^=$ which occur in the soil solution. Both forms are present in soils that are neutral to alkaline (pH 7.0 - 7.8) and the proportion of $HPO_4^=$ ion increases as pH increases.

Forms of Soil Phosphorus

The total amounts of phosphorus found in a soil may range from 200 to 3,400 pounds of P per acre. The usual range of soil phosphorus, however, is 800 to 1,600 pounds of P per acre. At first glance, this may seem to be enough phosphorus to produce good crops. However, as will be explained later, only a very small amount of the total phosphorus is available for plant growth. In most soils only 2 to 3 pounds of P is available for plant growth at any one time.

Soil phosphorus can be divided into two broad groups, the first being *organic phosphorus*. Like nitrogen, organic phosphorus is concentrated in the top soil where the organic matter levels are highest and must be mineralized before the phosphorus can be used by plants. Under favorable conditions, organic phosphorus can become a significant source of the nutrient for plant growth. However, organic phosphorus usually is not considered to be of much significance in North Dakota soils.

Some of the *inorganic phosphorus,* the second group, reacts with clay, organic matter, iron, aluminum, calcium and other soil constituents. Some of these reactions result in unavailable phosphorus while others are available to different degrees. Factors such as pH, clay type, organic matter, amounts of phosphorus, etc., determine which reactions will take place in a particular soil and what forms of phosphorus can be expected.

Inorganic phosphates occurring in North Dakota soils are mainly calcium phosphates (predominant forms in alkaline and calcareous soil) such as:

1. Fluor-apatite $3Ca_3(PO_4)_2 \cdot CaF_2$
2. Carbonate-apatite $3Ca_3(PO_4)_2 \cdot CaCO_3$
3. Hydroxy-apatite $3Ca_3(PO_4)_2 \cdot Ca(OH)_2$
4. Oxy-apatite $3Ca_3(PO_4)_2 \cdot CaO$
5. Tricalcium phosphate $Ca_3(PO_4)_2$
6. Dicalcium phosphate $CaHPO_4$
7. Monocalcium phosphate $Ca(H_2PO_4)_2$

In most alkaline soils having a high pH, *chemical precipitation* of relatively insoluble dicalcium phosphate and other basic calcium phosphates is favored.

Phosphate ions coming in contact with solid phase calcium carbonate are precipitated on the surface of these particles. The amount of precipitation is influenced by the amount of surface exposed by the $CaCO_3$ and the concentration of P in solution.

Most calcium phosphates are insoluble in water and the phosphate is in a relatively unavailable form. However, in the mildly acidic conditions produced around plant roots, due to root excretions, calcium phosphates are more soluble and thus more of the phosphorus is available to plants.

Water soluble phosphorus is the major form available for plant growth. Plants absorb phosphorus from the soil solution in proportion to the concentration of phosphate ions in solution and growth will be proportional to amounts of phos-

phorus absorbed. Under field conditions the many forms of phosphorus approach chemical equilibrium with each other as illustrated:

Water soluble ⟷ Absorbed ⟷ Insoluble
phosphates ⟶ phosphate ⟶ phosphates

This equilibrium results in some of the fertilizer phosphorus added in water soluble forms being converted (fixed) to the less available forms.

Iron and aluminum phosphates (predominant forms in acid soils) are of minor importance in North Dakota soils.

Phosphorus adsorbed to soil particles by the above chemical precipitation processes or by more complex processes (Soil Fertility and Fertilizers, 1966) will be lost from the field when erosion removes the soil particles.

Behavior of Phosphate Fertilizers in Soils

The reactions taking place in the soil and the properties of the various phosphate fertilizer materials combine to determine the effectiveness of any source of phosphorus under any set of soil and cropping conditions. Fertilizer particle size, water solubility and placement of the phosphate material with respect to the seed determine the effectiveness of the fertilizer. In calcareous soils most of the phosphate is precipitated as dicalcium phosphate on the surface of calcium carbonate particles.

Relatively little, often less than one half of one per cent, of the native soil phosphorus is available to plants in any one growing season. The fate of fertilizer phosphorus, because of soil absorption or *fixation* (formation of unavailable phosphorus compounds in the soil) is not much better. It is not uncommon for only 5 to 10 per cent of the added phosphorus to be taken up by the first crop to which it was applied. This percentage may go as high as 40 per cent under very favorable conditions, but this is uncommon. Fixation can be reduced by minimizing the area of contact between the fertilizer and the soil. Granules present much less surface for contact per unit for phosphorus than do equal amounts of pulverized fertilizer. Banding further reduces contact and, thus, fixation is reduced or delayed.

As one fertilizes at higher rates, fixation of phosphorus becomes less of a concern. As more of the soils' soluble iron, aluminum, or calcium reacts with phosphorus, less remains to fix the additional applied P. Therefore, at high levels of crop production one should not be too concerned about "fixation." The soluble fertilizer phosphorus applied and not recovered by the crop reacts mostly with soil calcium in our North Dakota soils. Accumulation from repeated applications of phosphorus results in increasing the level of plant available phosphorus in the soil.

Phosphate Fertilizers

During the past few years we have seen not only a rapid increase in the use of phosphate fertilizers, but also a great change in the fertilizer industry and many different fertilizers coming into the market. The primary phosphorus fertilizers used in North Dakota are as follows:

Name of Fertilizer	Chemical formula	Usual analysis	Form
Super-phosphate	$Ca(H_2PO_4)_2$	0-45-0	solid
Mono-ammonium phosphate	$NH_4H_2PO_4$	11-48-0	solid
Diammonium phosphate	$(NH_4)_2HPO_4$	18-46-0	solid
Ammonium poly-phosphate	$NH_4H_2PO_4$+ $(NH_4)_3HP_2O_7$	10-34-O 15-62-0	liquid solid

Looking at the means used to produce various phosphorus fertilizers will help one understand what form of P is being added to the soil when these materials are used.

Rock phosphate contains apatite as the phosphate compound and is either heat or acid treated to make the phosphate more soluble. The acid treatment is the more important group of commercial fertilizer phosphates.

Phosphoric Acid - This material is produced by treating rock phosphate with sulfuric acid (H_2SO_4) or by burning elemental phosphorus, forming P_2O_5 and reacting with water. So called *green* or *wet acid* results from the H_2SO_4 treatment; *white* or *furnace acid* from the burning process.

Agricultural phosphoric acid contains 24% P (55% P_2O_5). It can be used to acidulate additional rock phosphate to make triple super-phosphate, neutralized with ammonia (NH_3) to manufacture ammonium phosphates and liquid fertilizer or used directly as a fertilizer.

Superphosphoric Acid - This product is produced by *dehydrating* (removing water) from green acid or furnace acid. It is completely water soluble and contains 34% P (79% P_2O_5). Superphosphoric acid contains 35 to 50 per cent of such condensed phosphate radicals as pyro-, tri- and tetrapoly-phosphates. It is used primarily for the manufacture of ammonium and calcium polyphosphates.

Calcium Orthophosphates - The most important phosphate fertilizers consisting of calcium orthophosphate are ordinary superphosphate containing

7 to 9% (16-22% P_2O_5), triple or concentrated superphosphate containing 19 to 23% (44-52% P_2O_5) and ordinary and triple superphosphates that have been reacted with ammonia to form ammoniated superphosphates.

The superphosphates are slightly acidic fertilizers, but have no appreciable effect on soil pH. Ammoniated superphosphates produce a slightly acidic soil reaction.

Ordinary superphosphate (OSP) is made by reacting sulfuric acid with rock phosphate. The product of the reaction is essentially a mixture of monocalcium phosphate and gypsum. About 90% of the phosphorus is water soluble and essentially all is classed as available. OSP also contains 8 to 10% sulfur as calcium sulfate.

Triple or concentrated superphosphate (CSP) is made by treating rock phosphate with phosphoric acid. The resulting product is mostly monocalcium phosphate containing 19 to 23% P (44-52% P_2O_5).

Ammonium Phosphate - This fertilizer material is produced by reacting different amounts of ammonia, phosphoric acid and sulfuric acid. The most common ammonium phosphate fertilizers are monoammonium phosphate (MAP), diammonium phosphate (DAP), and ammonium phosphate-sulfate (16-20-0). The most common, MAP, is 11-48-0; 16-48-0 and 18-46-0 are the most common DAP materials.

Ammonium phosphates are completely water soluble, are excellent sources of both nitrogen and phosphorus, have a relatively high plant-food content which minimizes shipping, handling and storage costs, and good handling properties. All of the factors combine to make these phosphate materials very popular. They are used for formulating solid fertilizers, in manufacturing liquid materials, and by direct application as starter fertilizers.

Ammonium Polyphosphate - This is a mixture of ammonium salts of simple and complex phosphoric acids. This material is increasing in importance, and is common in liquid fertilizers here in North Dakota.

Phosphorus Summary

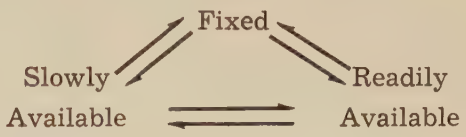
Conversion of water soluble phosphorus added as commercial fertilizer to insoluble forms doesn't allow phosphorus to be moved much by water. The insoluble forms are lost if soil erosion occurs.

C. Potassium

This nutrient usually is expressed as potassium oxide (K_2O) in fertilizer analyses, but is not in that form in fertilizer or taken up by plants in this form. The oxide use is a carryover from the time when analytical procedures oxidized potassium.

Except for what has been added in fertilizer, the potassium in soils comes from rocks containing minerals bearing potassium. Some of the secondary and clay minerals in soils also contain potassium. It is present in these forms in rather large amounts in most North Dakota soils and as a result not much has been added from commercial fertilization.

Potassium is taken up by plants as the potassium ion (K^+) from the soil solution or directly from the cation exchange complex. It exists in the soil as *fixed* (not available), slowly available and readily available forms. The equilibrium between these forms is illustrated as follows:



The fixed portion is not available to plants and is a part of unweathered or slightly weathered minerals. The slowly available potassium is associated with minerals which alternately release or fix potassium. Readily available potassium is present in the soil solution or held on the cation exchange positions of clay minerals and organic matter as the positively charged K^+ ion.

Since the readily available potassium is attracted to the negative charge on soil components it normally is not subject to much movement. If a soil has low cation exchange capacity, the excess K^+ can move with water. For most soils in North Dakota there is usually enough negative charge present to keep the K^+ associated with soil particles. Should these soil particles be removed as a result of soil erosion, the K^+ associated with them also is lost.

Potassium Fertilizers

Potassium chloride ($KC\ell$), commercially called muriate of potash, is mined and used as the primary potash fertilizer in the state. Some sulfate of potash (K_2SO_4) is also used as a potash source.

The characteristics of these materials are as follows:

Name of fertilizer	Chemical formula	Usual analysis	Form
Muriate of potash	$KC\ell$	0-0-60	solid
Sulfate of potash	K_2SO_4	0-0-50	solid

Both of these materials go into solution in the soil (readily available form) to supply the K^+ ion for plant uptake and soil reactions.

Potassium Summary

Potassium added in commercial fertilizer is not subject to much movement by water since it is attracted by the negative charge associated with soil particles and organic matter. Loss of soil particles by erosion does take the associated K+ with them.

V. SOIL MANAGEMENT PRACTICES

For a given soil, precipitation pattern and fertilization situation, movement of fertilizer constituents may be different owing to different soil managing practices. If we consider the movement of fertilizer solids, e.g., movement of relatively insoluble phosphate, a greater loss in the long run due to erosion would be expected on the field which is alternate crop-fallowed than for the same soil which is continuously cropped. Similarly, leaching of soluble nutrients would be expected to be greater for the alternate crop-fallow system as we shall see below.

A. Continuous Cropping

Let us first consider continuous small grain cropping. A small grain crop ceases to extract water from the crop rooting zone around mid-July to early August. A portion of the precipitation received as rain from this time until the soil surface freezes is stored in the soil profile. If precipitation occurs as light showers, most of it evaporates from the soil surface. If the rainfall event exceeds about one-fourth inch, water penetrates deep enough below the soil surface so that not all will be lost by evaporation from the soil. A weedy field will store only a small portion or perhaps none of the precipitation because of transpiration losses through the weeds. Potential evapotranspiration (PET) decreases rapidly toward the end of summer so that during the fall months a greater percentage of the precipitation is stored (Figure 4). During the spring, additional water is stored in the soil profile—again because PET is low and growing vegetation is absent. At planting time, considered here to be April, the 3-foot rooting zone may or may not be recharged completely. Some deep percolation may occur around May when precipitation is relatively high (Figure 1) and the crop, because of its small size, still extracts little water. Of course, deep percolation can occur at any time throughout the year if water enters the soil when the crop rooting zone is fully recharged. If deep percolation does occur, some leaching of soluble salts, including some of those added in commercial fertilizer, will occur.

Transpiration increases as the small grains grow larger and tiller. During this period precipitation tends to recharge the rooting zone, thus replacing that water extracted since the previous rainfall by roots of the growing crop. For the continuous small grain cropping system in sub-humid to semi-arid North Dakota, little deep percolation is expected during this period. As June wends into July, the small grain crop extracts water from the crop rooting zone at an increasing rate. Finally, as we complete the one-year cycle with swathing of the crop, the crop rooting zone is again depleted or nearly depleted of available water.

The above discussion considered only the average conditions observed in North Dakota. There are wet years and dry years during which the picture above changes somewhat. During a very wet year, deep percolation may occur several months, whereas in a dry year there may not even be enough water to produce a 10-bushel per acre yield of grain. No deep percolation would be expected in this case. In general, deep percolation losses are slight to none for dryland continuous small grain management systems.

The deep percolation process is only slightly different for a continuous row crop management system, e.g., for crops such as corn or sugarbeets. These crops continue to extract water from the rooting zone until September or October. Little water is stored in the root zone during this time since the row crop continues to lose water by transpiration, although at a decreasing rate. At freezeup, less water may be stored in the soil profile for the row crop than for the same soil continuously cropped to small grains. During May and June, when precipitation is heavy (see Figure 4), soils planted to row crops lose little water to transpiration so the water accumulates in the rooting zone. Since the rooting zone of corn and sugarbeets is deeper than that of small grains, the roots can extract water should it percolate a little deeper. For dryland conditions little leaching beyond the rooting zone of row crops is expected.

Even less water would be lost to deep percolation for a continuous grass or hay cropping system, as there is no time in early spring when the soil is bare (Powers, 1970). Moreover, no lengthy time is required for root development as with annual crops. Thus, forage crops tend to use stored soil water during spring, summer and fall if it is available.

B. Alternate crop-summerfallow

During a two-year crop-summerfallow cycle the soil has little or no growing vegetation on it for a period of 18 to 21 months. For a small grain crop, this period usually begins in August and ends in May, more than one year later. During this period 15 to 30 inches of precipitation may fall upon the soil surface. The efficiency of water storage by fal-

low is about 20% for this period with most of the water being stored in the soil the fall of the first year (Haas and Willis, 1962). Precipitation falling on the bare soil the next spring, summer and fall may result in appreciable runoff and associated soil erosion. Loss of soil fertility is inherent in the erosion process as both dissolved and solid fertilizer materials as well as organic matter and soil particles are removed. A portion of the precipitation received during the fallow period may percolate below the rooting zone, carrying dissolved solutes with it. Since nitrate-nitrogen is released from organic matter, some of it is leached deeper into the soil profile and, finally, out of the rooting zone. Most of the nitrogen leached from fallow soils originates from mineralization of nitrogen from organic matter and decomposition of crop residues during the fallow period, rather than from fertilizer materials.

C. Irrigation

Management practices become especially important when irrigation is practiced. In general, irrigated soils are subject to leaching from early spring to late fall. Scheduling each irrigation and applying the correct amount of water at each irrigation are important considerations. Fertilization practices must be compatible with the chosen irrigation program and selection of the form of fertilization materials becomes more important. An unexpected heavy rain closely following an irrigation which recharged the root zone could result in the leaching of soluble anions such as nitrate. A rain such as this could occur any time during the growing season.

For sustained irrigation agriculture, leaching is necessary to remove salts added in irrigation waters. To minimize fertilizer leaching losses, these operations should be performed when the amount of mobile nutrients is at a minimum, such as in the fall.

VI. FERTILIZER MOVEMENT UNDER FIELD CONDITIONS

In order to understand fertilizer movement under North Dakota conditions, we will analyze the fertilizer movement for several fertilizer situations. Recall that fertilizer movement is affected by nature of the fertilizer, nature of the precipitation, soil properties and the soil management system. Before proceeding further, we must necessarily make a few assumptions regarding the above factors. In the discussion which follows, two soil textures will be considered (see Table 3)—a loamy sand (coarse-textured soil) and a clay loam (moderately fine-textured soil) and it will be assumed that the texture is the same throughout the profile. The loamy sand stores 0.8 inches available water per foot of soil; the clay loam, 2.0 inches per foot (Figure 5). In addition, we will assume that these soils are under a continuous small grain management system. Furthermore, mean values of precipitation, as shown in Figure 1, will be assumed. When we use these assumptions, we necessarily limit our discussion to fertilizer movement under these, and only these, conditions. However, once we understand fertilizer movement for these conditions, it is a relatively simple matter to project results for different soils, different soil management systems and to allow for deviation of precipitation from the normal.

DRYLAND - CONTINUOUS SMALL GRAINS

We begin our analysis in late July, immediately after swathing of small grains. At this time the 3-foot deep rooting zone is depleted or nearly depleted of available water. By Sepember 1, 1 to 2 inches of available water may be stored and by freeze-up time, 2 to 3 inches. No water is stored during the winter when the soil surface is frozen, but 1 to 2 inches may be stored following the spring thaw. By seeding time, in mid-April, about 3 inches of water may be stored. For the ensuing discussion, let us assume the amounts of available water stored in the rooting zone at various dates are those presented in Table 5. The values at seeding time are derived from stored soil moisture data collected throughout North Dakota for the 1958-61 period (Bauer et al., 1967). These data, translated into depth of water

Table 5. Estimated Available Water Stored in Rooting Zone for Continuous Small Grains at Several Dates

Date	Amount Stored (in.)
harvest	0
September 1	1.7
freeze-up	2.2
March 1	2.9
planting*	3.3

*Based on data from Bauer et. al., 1967.

movement in the loamy sand and clay loam soils, are depicted in Figure 9. The depth to which these amounts of water have penetrated these two soils for the different dates are shown. The same amount of available water is stored in each soil profile; because the available water holding capacity of the loamy sand is only 0.8 inches per foot, a greater volume of soil is required to hold a given amount of available water compared with the clay loam. With this water regime in mind, we can now proceed with our analysis.

CASE A. Application of ammonium phosphate and potash immediately after harvest

This fertilizer situation is not often encountered in North Dakota. It is included for sake of completeness and appears as our first case so it can be compared with some of the more common cases which follow.

Essentially all of the water stored in the soil profile occurs after application and incorporation of the fertilizer materials. Figure 10 shows the depth to which water penetrates and the position of N, P and K at seeding time. The $HPO_4^{=}$-P remains in the incorporated zone, since it behaves according to the discussion in Section IV. K^+ also is adsorbed and remains *immobile* (does not readily move with water). Since the ammonium phosphate was applied long before it turned cold in the fall, soil temperatures were favorable for nitrification, resulting in the conversion of NH_4^+-N to NO_3^--N. The NO_3^--N being mobile, moves with the penetrating water. Some leaching of mobile NO_3^--N below the rooting zone occurred for the loamy sand but not for the clay loam.

CASE B. Fall application of ammonium phosphate and potash

Fall is arbitrarily defined as the period from October 1 to freeze-up. Figure 11A shows the depth to which soil water is stored in each soil at the time of the fall application of $(NH_4)_2HPO_4$ and KCl while Figure 11B shows the depth of water storage and the fertilizer distribution at planting time. Since the NH_4^+-N was applied when the average soil temperature in the upper 6 to 12 inches of soil remained below 50°F, virtually no biological conversion of NH_4^+-N to NO_3^--N occurred as for Case A. Consequently, NH_4^+-N remains adsorbed to clay surfaces. For this case, no leaching of N, P or K occurs in either the loamy sand or the clay loam.

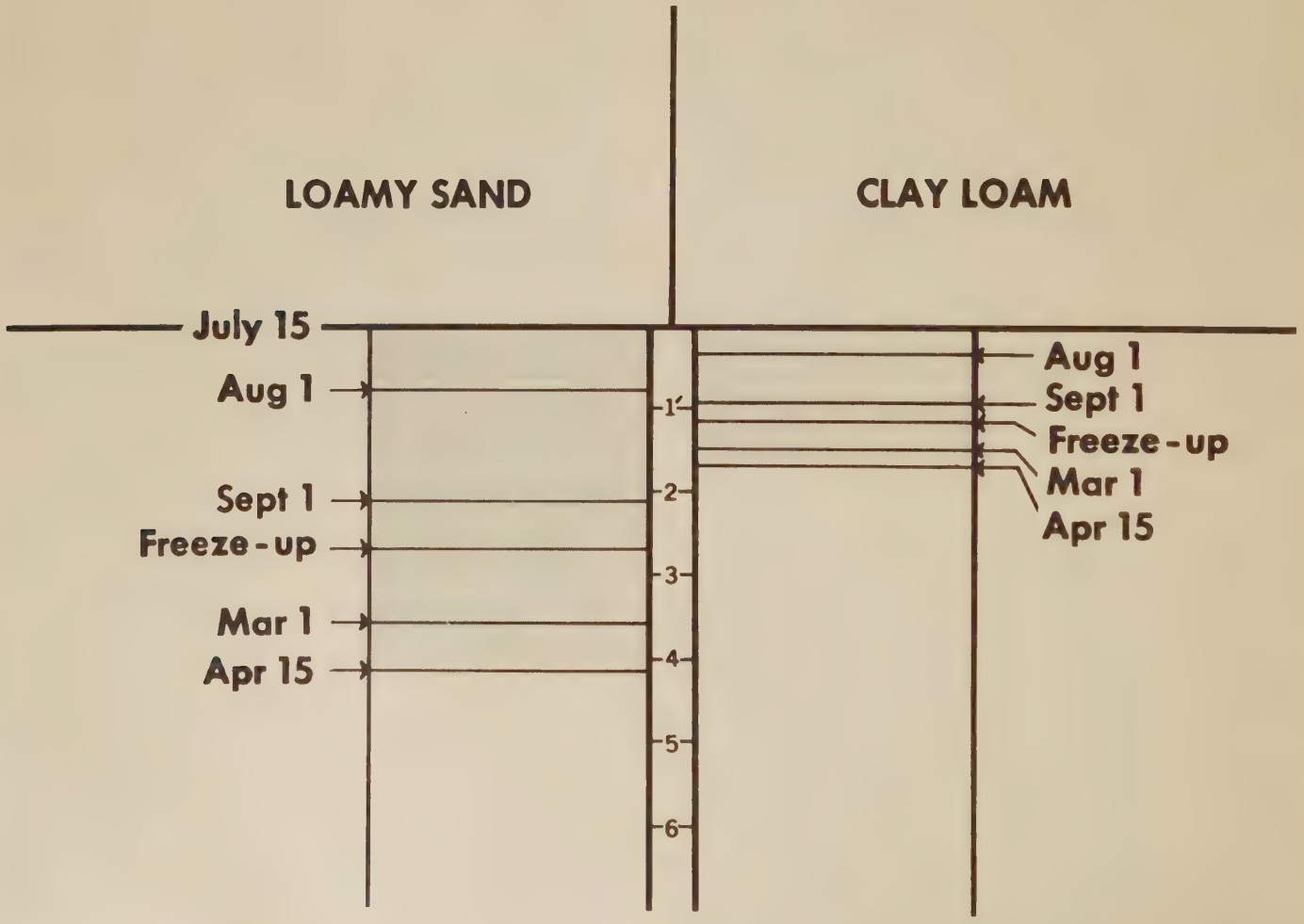


Figure 9. Depth to which precipitation has penetrated loamy sand and clay loam soils for selected dates. The soils had no stored available water on July 15.

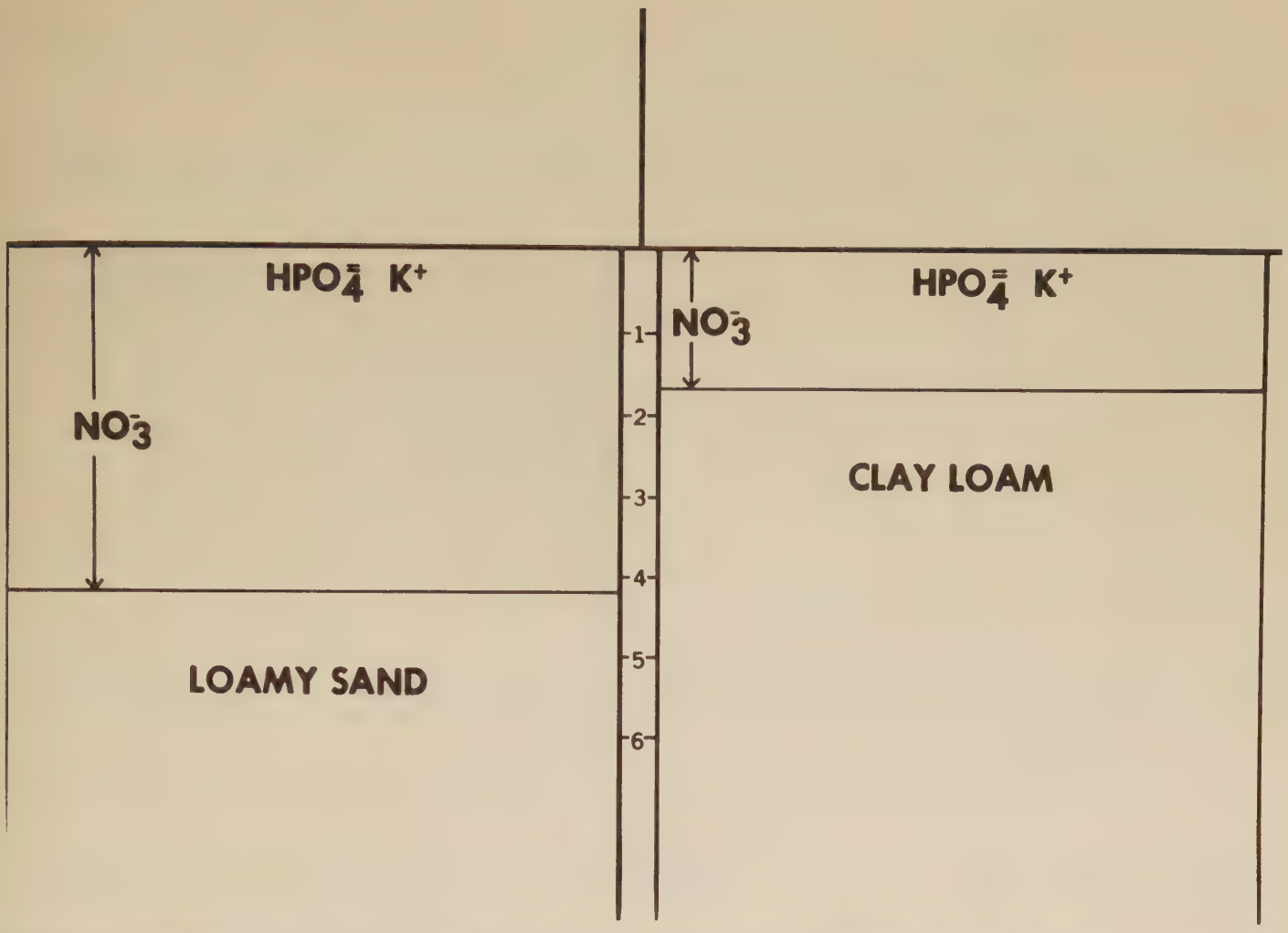


Figure 10. Depth of soil water penetration and position of N, P and K at seeding time for application of ammonium phosphate and potash immediately after harvest. No available soil water was present in rooting zone the date of fertilizer application.

CASE C. Late summer application of ammonium nitrate

Late summer is arbitrarily defined as August 1 to September 1. After application of NH_4NO_3, the NH_4^+-N is adsorbed to clay particles while the NO_3^--N remains mobile. Since the temperature in the upper 6 to 12 inches of soil is still warm, biological conversion of NH_4^+-N to NO_3^--N occurs if the soil is moist. Within a period of 4 to 8 weeks after application, much of the N added as NH_4NO_3 exists in the mobile nitrate form and will move with water. Figure 12 shows (a) depth of water penetration at fertilization, and (b) depth of NO_3^--N penetration at planting time.

CASE D. Late summer application of anhydrous ammonia

Recall that *late summer* is arbitrarily defined as August 1 to September 1. Immediately upon injection of anhydrous ammonia (NH_3), it reacts with the soil water to form ammonium NH_4^+-N which in turn is adsorbed by clay particles. Since soil temperatures are warm, the NH_4^+-N is converted to NO_3^--N by microbial activity. Depth of movement of the resulting NO_3^--N at planting time is nearly identical to that for Case C and is shown in Figure 12.

CASE E. Fall application of ammonium nitrate, ammonium phosphate and potash

Figure 13 shows the distribution of N, P and K at planting time. The water content distribution at the time of fertilizer application is identical to Case B and is shown in Figure 11A. Although soil temperatures in the upper 6 to 12 inches of soil remained below 50°F after application, mobile NO_3^--N is present because it was applied to the soil in this form. After fertilization, water infiltrating the soil (primarily in the spring) moves the NO_3^--N downward while K^+ and $HPO_4^=$-P and NH_4^+-N remain

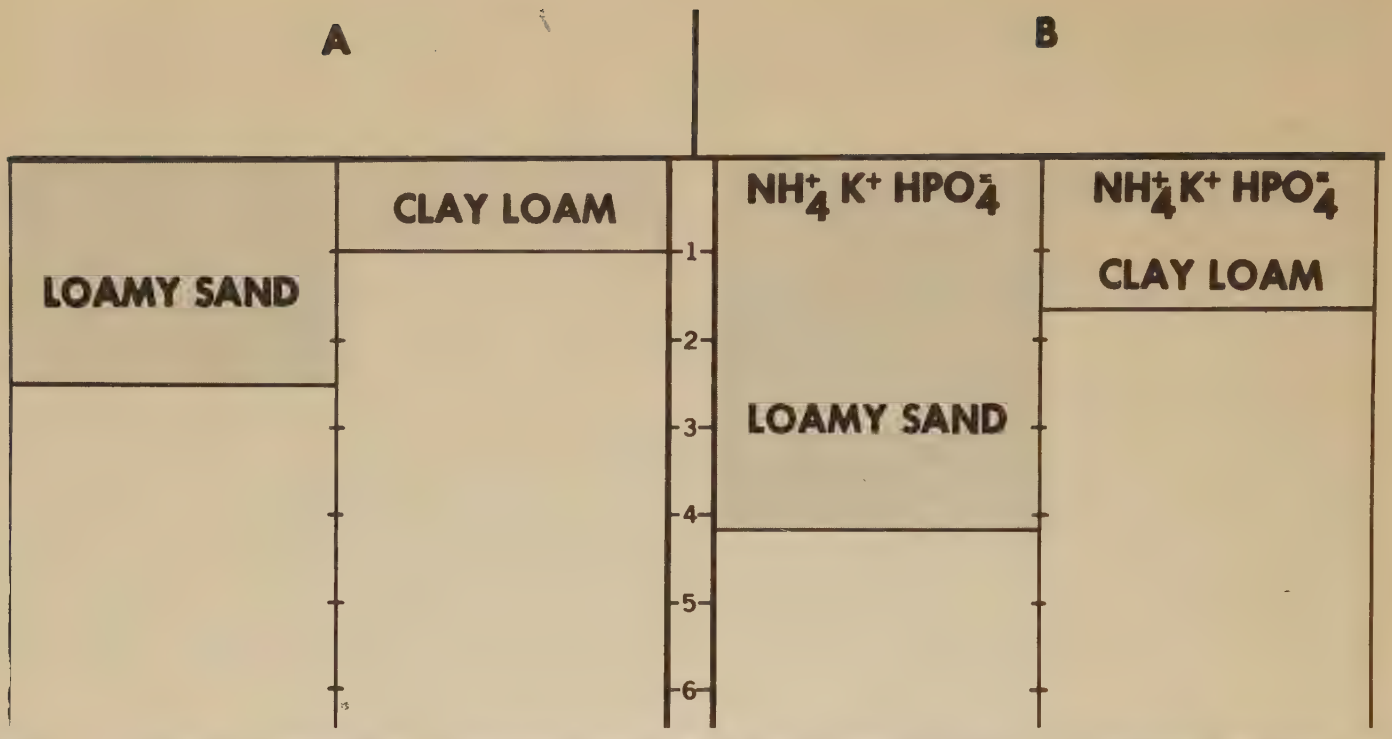


Figure 11. A. Depth of penetration of available water at the time of late fall (Oct. 1 - freeze-up) application of ammonium phosphate and potash on loamy sand and clay loam soils under a dryland continuous small grain management.

B. Depth of water penetration and location of N, P and K for the same soils at seeding time (April 15).

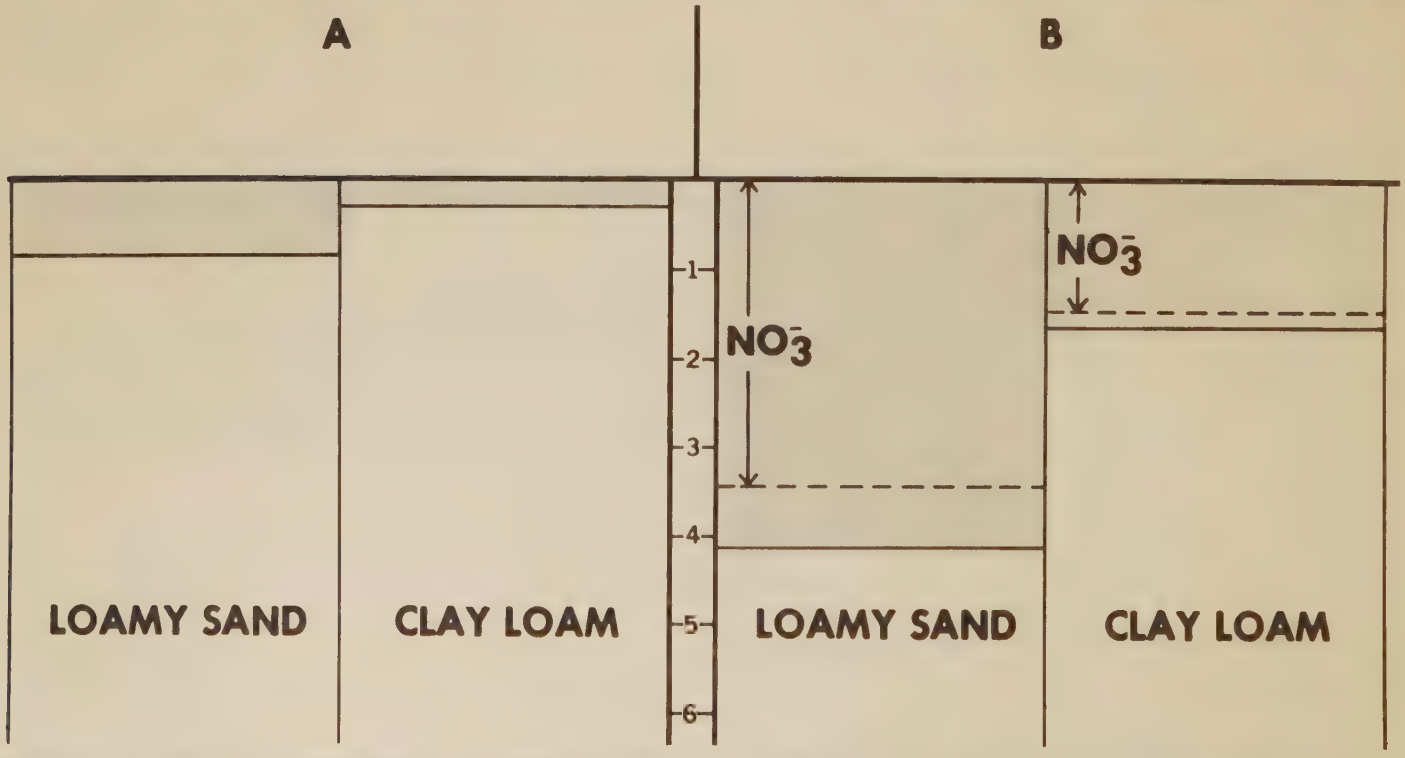


Figure 12. A. Depth of penetration of available water at time of late summer (August 1 - September 1) application of ammonium nitrate to loamy sand and clay loam soils under a dryland continuous small grain management system.

B. Depth of penetration of available water and the N distribution for the above soil at seeding time (April 15).

adsorbed to soil particles in the zone of fertilizer incorporation. Notice that NO_3^--N did not leach below the root zone for either soil, but remained in the upper two feet. Should heavier than normal spring rains occur before planting or even up to 3 or 4 weeks after planting, some loss of NO_3-N below the rooting zone in the loamy sand might occur.

CASE F. Late fall application of anhydrous ammonium

Upon injection, NH_3 combines with water to form ammonium NH_4^+ which in turn is adsorbed by clay particles. Since soil temperatures in the injection zone are less than 50°F little nitrification of the absorbed NH_4^+ occurs. The planting time distribution of N that was injected as NH_3 in late fall is identical to that for a late fall application of NH_4^+ and is shown in Figure 13.

CASE G. Winter application of any kind of fertilizer on frozen soils

Although labor may be plentiful at this time of the year, it is an extremely poor time to apply any kind of fertilizer to soils. The fertilizer material remains on the soil surface or on snow until the soil and/or snow thaws. During the spring thaw some of the fertilizer material may infiltrate the soil surface. A large fraction of the fertilizer material probably will dissolve and be carried off in runoff waters. Potassium and $HPO_4^=$-P are subject to considerable loss in the runoff waters (Timmons et al., 1968). Consequently, a significant portion of it may reach streams, thus constituting a financial loss to the farmer in addition to degrading water quality. Winter application of fertilizer is a poor practice even for soils which drain into closed depressions or potholes. In this case fertilizer materials are removed from the steeper land areas (the low fertility areas) and transported to the lower, wetter areas where it may not even be feasible to till. Leaching of winter applied nitrate, should it infiltrate the soil surface, would be similar to that shown in Figure 13.

In summary, winter application under North Dakota conditions of any fertilizer, including manure, is a poor management practice.

CASE H. Early spring application of anhydrous ammonia

Early spring injection of NH_3 gives results similar to those for the late fall application of NH_3 of Case F.

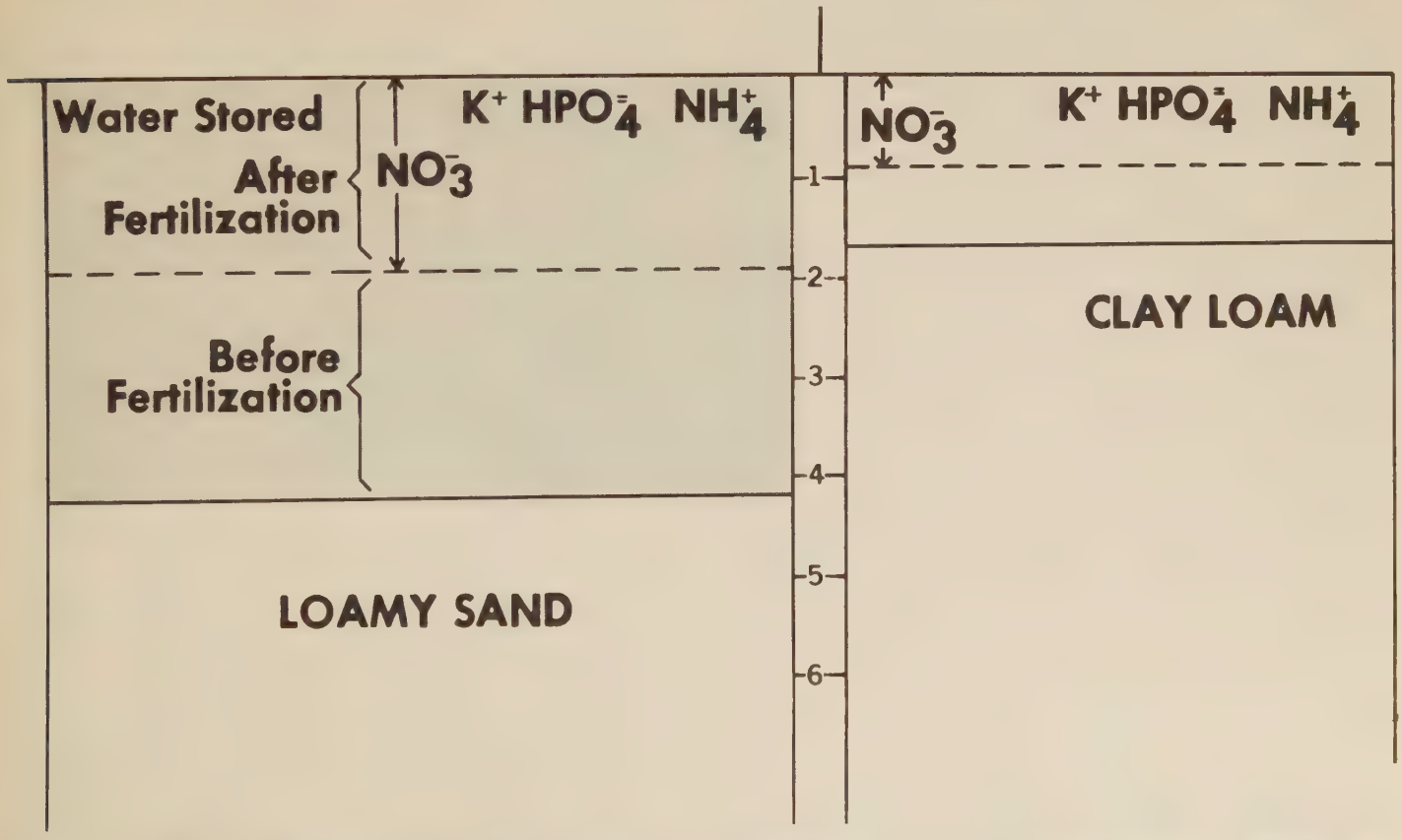


Figure 13. Depth of penetration of available water and the position of N, P and K in the soil profile at seeding time (April 15) for a late fall application (October 1 - freeze-up) of ammonium nitrate, ammonium phosphate and potash to loam sand and clay loam soils under a dryland continuous small grain management system.

CASE I. Seeding time application of ammonium phosphate, potash and either ammonium nitrate or anhydrous ammonia

For this case, the fertilizer materials should be incorporated or put "down the spout" a short distance from the seed. Anhydrous ammonia and the NH_4+-N are converted to mobile NO_3^--N. However, the fertilizer constituents and their derivatives remain at or near the site of incorporation and, with the exception of phosphorus, are soon extracted by plant roots.

CASE J. Late summer application of urea

Urea ($CO(NH_2)_2$) applied in late summer behaves similarly to late summer applied NH_4^+-N (Case A) and its distribution in the soil at seeding time will be the same as shown in Figure 10. Upon late summer application of urea to soils, the urea-N is rapidly converted to NH_4^+-N which is adsorbed to soil particles. This conversion is not a microbial transformation like the conversion of NH_4^+-N to NO_3^--N, but is, instead, a chemical process. After this chemical conversion, however, microbial transformation of NH_4^+-N to NO_3^--N does occur until soil temperatures in the incorporation zone decrease to below 50°F.

One word of caution is in order. Urea must be incorporated into the soil soon after application (preferably within 2 to 3 days) to prevent possible gaseous loss of NH_3 *(volatilization)* during the period when it is converted to NH_4^+-N. This potential volatilization loss is especially important on limey soils but may occur to some degree on all soils.

CASE K. Late fall application of urea

The urea-N is chemically converted to NH_4^+-N, which is adsorbed on soil particles. Since soil temperatures are below 50°F, little conversion of NH_4^+-N to NO_3^--N occurs. The N distribution in the soil profile at seeding is identical to that shown in Figure 11B. Again, incorporation of urea is essential.

CASE L. Seeding time application of urea

The urea must be incorporated into the soil to prevent excessive volatilization losses. The urea-N is rapidly converted to NH_4^+-N, which is adsorbed. Behavior of the N is then identical to the N discussed in Case I; i.e., seeding time application of NH_4^+-N.

DRYLAND - CONTINUOUS ROW CROPS

For cases A through L above, we have considered only a dryland continuous small grain management system where the soil ordinarily is depleted of available water to about 3½ feet. The soil profile ordinarily is depleted of available water to a greater depth (to 4 or 5 feet) for row crops. Moreover, row crops are harvested later and soils planted to them do not store as much available water at freeze-up time as do identical soils under a continuous small grain system. To compare the continuous row crop (corn) with the continuous small grain management system, let us consider a late fall fertilizer application.

CASE M. Late fall application of ammonium phosphate, ammonium nitrate and potash

The distribution of water in the soil at the time of application and the water storage and position of N, P and K at seeding time are presented in Figure 14. The same fertilization situation under continuous small grains is shown in Figure 13. Less available water is stored for row crops at the time of fertilizer application; hence, at seeding time any mobile nutrients will be positioned at a shallower soil depth. Figure 14 shows that the N applied as NO_3^--N is distributed to nearly 2 feet in the loamy sand and to about 1 foot in the clay loam. The remainder of the fertilizer nutrients remain adsorbed or fixed at their site of incorporation. Rainfall after seeding may move NO_3^--N deeper, but almost always not out of the rooting zone.

IRRIGATED SOILS - ROW CROPS

The acreage of irrigated soils in North Dakota is increasing annually. Many soils brought into irrigation are coarse to moderately-coarse textured. Such soils benefit greatly from irrigation water, as these soils are normally drouthy. In addition, these drouthy soils typically have low CEC values; i.e., not much storage for the cations such as K+, NH_4^+ and Ca++. Excess water percolating through soils of this nature can remove some cations if they are present in amounts in excess of the CEC. On the other hand, it is easy to *over-irrigate* (add too much water) these soils which have low available water holding capacities. Over-irrigation results in leaching of mobile nutrients, such as NO_3^-, if they are present, as well as possibly leaching out such nutrients as K+ and NH_4^+.

Case N. Application of anhydrous ammonia, ammonium nitrate or urea near seeding time on irrigated soils

The ammonium forms of N are soon biologically converted to NO_3^--N, which is mobile. As the row crop develops, a water shortage develops and irrigation becomes necessary. At each irrigation an attempt is made to replenish that water previously extracted from the rooting zone. If no large rainstorms follow irrigations, and if the level of water management on the part of the irrigator is good, all fertilizer nutrients remain in the crop rooting

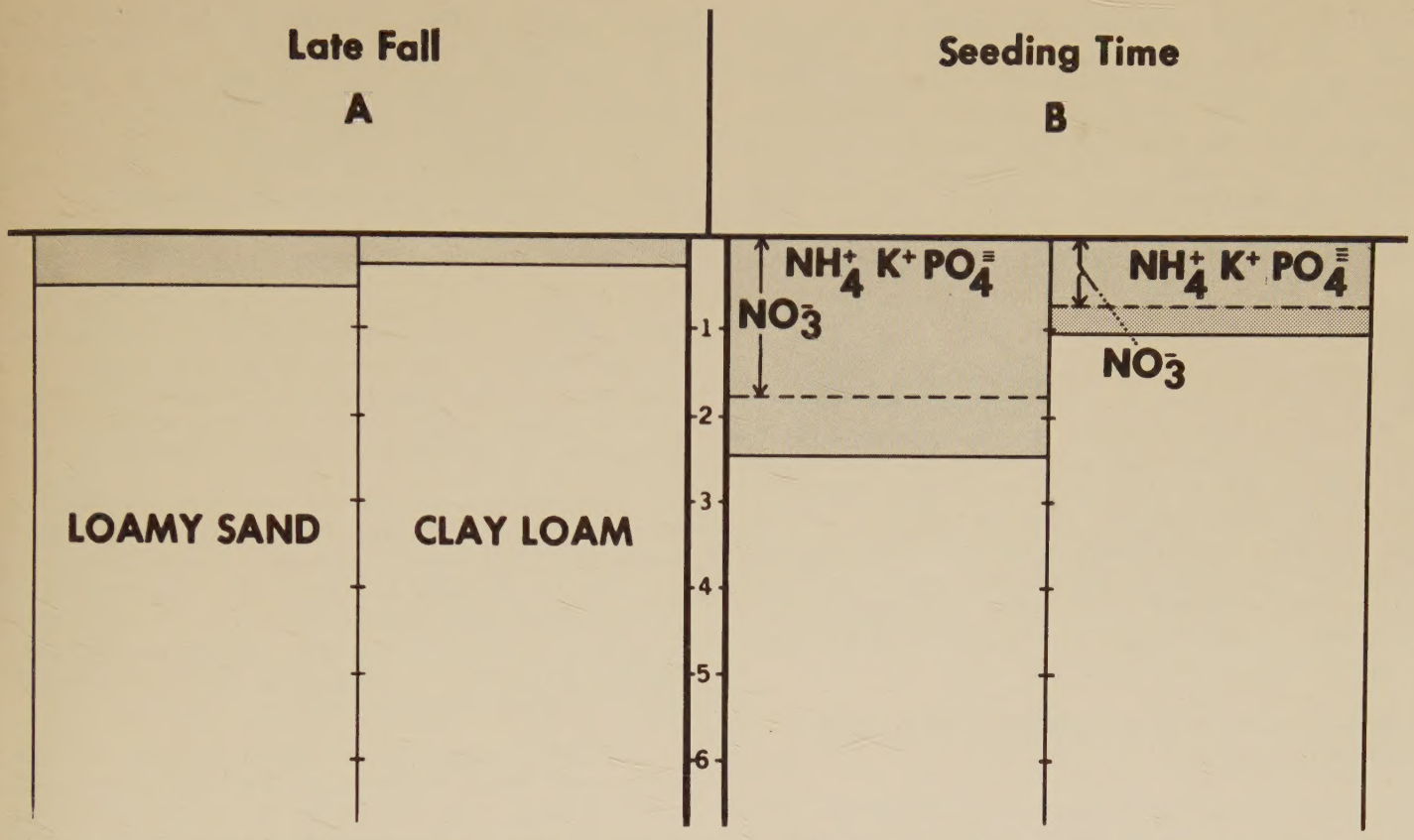


Figure 14. A. Depth of penetration of available water at time of late fall (October 1 - freeze-up) application of ammonium phosphate, ammonium nitrate and potash to loamy sand and clay loam soils under a continuous row crop management system.

B. Depth of penetration of available water and the position of N, P and K in the soil profile at seeding time (May 1 - May 20).

zone. If over-irrigation should occur, leaching occurs in a manner directly proportional to the amount of excess water added.

CASE O. Split application of nitrogen on irrigated soils

If a portion of any nitrogen fertilizer(s) is applied at seeding time and a second or third application made periodically during the growing season at times when the plant's need for N increases, the chances for leaching losses of N decrease. By fertilizing at times when the crop's requirements for nutrients are greatest, no appreciable excess of leachable NO_3^--N is permitted to accumulate in the soil. The additional applications of N during the growing season can be broadcast, side-dressed, top-dressed or applied in sprinkler irrigation water. In any case, the NO_3^--N penetrates the soil only as deeply as the irrigation water following the application.

SUMMERFALLOW

Concern by farmers as well as researchers has increased recently over the movement of nitrates in fallow soils. As indicated in Section V, some water percolates below the rooting zone under fallow conditions. While virtually no one applies N fertilizer before or during the fallow period (and such a practice is definitely not recommended), residual NO_3^--N is present in the soil. In addition, NO_3^--N is released by microbial decomposition of organic matter and plant residues during the fallow period. The NO_3^--N is mobile and is thus subject to leaching. As water percolates below the rooting zone, some of the nitrate is carried with it. The high nitrate content of waters appearing at the soil surface at "saline seeps" in western North Dakota are possible evidence of this leaching process.

EFFECT OF VARIABLE PRECIPITATION

For all fertilizer regimes above (Cases A through O), normal precipitation (Figure 4) has been assumed. Very few years with seemingly normal precipitation occur. Some years may have heavy fall precipitation and light spring and summer precipitation, but yet total precipitation for the year will be very close to the mean annual precipitation shown in Figure 1. Then, too, there are wet years and dry years, years with heavy snowfall, years

with little fall precipitation but heavy summer rainfall. The vagaries of the weather are too complex to consider fertilizer movement for all cases. However, with knowledge of monthly precipitation coupled with the potential evapotranspiration (PET) in Figure 4, one can predict the depth of water movement and the fertilizer movement for specific soils, fertilizer situations, and soil management practices in the same manner as for Cases A through O above.

SOILS

Not all soils are loamy sands or clay loams; i.e., other soil textures exist than those considered in Cases A through O above. Fertilizer movement in these soils can be estimated, using the information in Section III. From Figure 5, one can obtain the available water holding capacity per foot of soil. If the soil under consideration does not fall into the coarse or moderately-coarse textural class (Table 3), one can assume that the cation exchange capacity is great enough to prevent leaching of fertilizer cations such as NH_4+ and K+.

MOVEMENT OF MATERIALS OTHER THAN FERTILIZERS

In the discussion above, only fertilizers have been considered. In our highly technical agriculture other materials such as herbicides, insecticides and fungicides often are added to soils. These materials or their derivatives also are subject to erosion losses and possibly to leaching losses. Whether leaching losses will occur depends upon the chemistry of the material as well as the other factors considered in Sections II through IV. One particular herbicide may be strongly adsorbed by organic matter within a soil while a second herbicide may not react at all with organic matter. Leaching of the herbicide in this case would depend, in addition to the factors discussed previously, upon the amount of organic matter present. Since the chemical nature of pesticides, soil conditions, etc., are different, no general predictions regarding their behavior in soils for this group of materials as a whole can be made.

Summary

Movement of fertilizers in North Dakota soils is a complex process depending upon such factors as the nature of the fertilizer, nature of the soil, the weather and management practices. Circumstances govern which of the above factors are most important for any given fertilizer situation.

Water-caused soil erosion and leaching are the two methods accounting for nearly all fertilizer movement in our soils. Through soil erosion we lose not only the valuable soil itself but also phosphates, ammonium-N and other plant nutrients which are adsorbed to the soil particle. Moreover, unincorporated fertilizer materials lying on the soil surface also are removed by soil erosion.

Nitrate-nitrogen is the plant nutrient we are concerned about in terms of leaching. For sandy soils having very low cation exchange capacities, some leaching of cations such as potassium and ammonium may occur. The semi-arid climate of North Dakota is not conducive to leaching of our soils year after year. There are particular years, however, when climate, management and other factors are such that leaching does occur. The amount of leaching incurred depends upon the factors listed above. Leaching losses are more likely on irrigated or summerfallowed soils than for continuously cropped soils.

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APPENDIX

Table A. North Dakota Fertilizer Sales by Grade and Materials, 1972 (State Laboratories Department, Bismarck, North Dakota).

Mixed Fertilizers	Jan.-June Tons	July-Dec. Tons	Total Tons
0-26-26	89		89
0-33-17	68	140	208
4-10-10	1,786		1,786
4-24-4	62		62
5-25-5	197		197
5-35-5	269		269
5-42-5	68		68
6-18-18	69		69
6-24-24	327		327
7-21-7	123		123
7-23-5	600	45	645
8-24-10	561		561
8-29-8	75		75
8-32-8		75	75
8-32-16	2,718	240	2,958
9-18-9	891		891
9-36-18		237	237
10-20-10	332		332
10-20-20	128		128
10-22-9	55		55
10-30-10	2,975	358	3,333
10-30-15	626		626
10-34-0	13,031	1,706	14,737
10-40-10	174	100	274
11-37-0	326	489	815
11-40-11		100	100
12-24-8	198		198
12-24-12	824	105	969
12-24-24	89		89
12-25-5	290		290
12-36-12	1,323	397	1,720
13-20-10	86		86
13-39-8	92		92
14-14-10	180		180
14-28-7	415	31	446
14-33-5	177		177
14-36-11	220		220
15-0-34	86		86
15-10-4	81		81
15-30-15	674	312	986
15-38-10	3,294	123	3,417
15-38-15		67	67
15-40-5	334	439	773
16-15-5	497		497
16-16-8	1,562		1,562
16-20-6	404	399	803
16-20-10	304		304
16-24-10	62		62
17-34-9	455		455
18-18-0	300		300
18-27-9	713		713
19-17-0	564		564
19-19-0	240		240
20-10-0	2,143		2,143
20-20-10		123	123
20-20-12	2,105	529	2,634
21-14-0	340		340
24-16-8	832	91	923
25-10-10		72	72
25-14-7	123		123
25-15-8	874		874
26-9-9		113	113
26-23-0	190		190
27-8-8	2,739		2,739
28-16-0	440		440
30-10-0	103		103
Miscellaneous	2,859	1,349	4,208
TOTAL	51,802	7,640	59,442

Fertilizer Materials	Jan.-June	July-Dec.	Total
	Tons	Tons	Tons
Ammonium Sulfate	3,758	551	4,309
Ammonium Nitrate	55,267	26,038	81,305
Ammonium Phosphate Sulfate (16-20-0)	878	518	1,393
Ammonium Phosphate (11-46-0)	293	182	475
Ammonium Phosphate (11-48-0)	8,891	7,789	16,680
Ammonium Phosphate (11-55-0)	4,684	2,705	7,389
Ammonium Phosphate (16-48-0)	918		918
Ammonium Phosphate (18-46-0)	49,739	47,305	97,044
Ammonium Phosphate (20-20-0)	192		192
Ammonium Phosphate (23-23-0)	1,453	1,609	3,062
Ammonium Phosphate (24-24-0)		274	274
Ammonium Phosphate (25-25-0)	4,594	1,119	5,713
Ammonium Phosphate (27-14-0)	380		380
Ammonium Phosphate (28-14-0)	147		147
Superphosphate 45%	263	575	838
Superphosphate 46%	5,735	4,816	10,554
Sewage Sludge	100	50	150
Urea	1,939	1,899	3,838
Ammonium Anhydrous	13,908	17,664	31,572
Nitrogen Solution 28%	23,435	11,070	34,508
Nitrogen Solution 34%		278	278
Potash	5,475	2,727	8,202
Miscellaneous Materials	87	150	237
TOTAL MATERIALS	182,136	127,319	309,455
MIXED FERTILIZERS	51,802	7,640	59,442
GRAND TOTAL	233,938	134,959	368,897

Annual Tonnage

1968	312,468 Tons
1969	327,712
1970	332,868
1971	340,635
1972	368,897

L. A. Koehler
State Food Commissioner & Chemist

April 1973

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